Modifying a Self-Sensing Circuit to Increase the Stability of Vibration Control

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Piezoelectric materials (PZTs) have properties that make it attractive as a sensor.

Advantages

Non-intrusive

Has potential for self-diagnostic capabilities

High Strain Sensitivity

Challenges

PZT is brittle

piezo.com

High electric fields are required (.5-2 MV/m)

Only low strains are obtainable

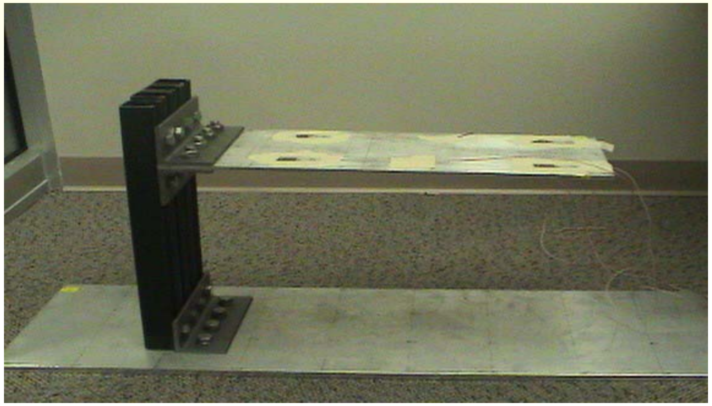
piezo.com

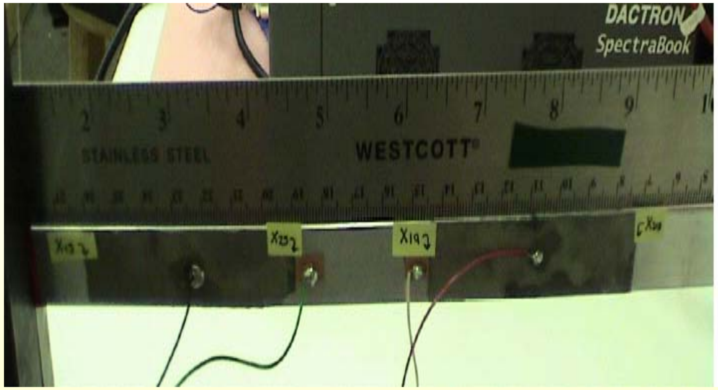
Advantages of piezoelectric self-sensing actuators.

Lighter and less costly than non-collocated systems.[Tani 2002]

The control force is applied where the response is measured.[Dosch 1992]

Unconditionally stable for feedback control.



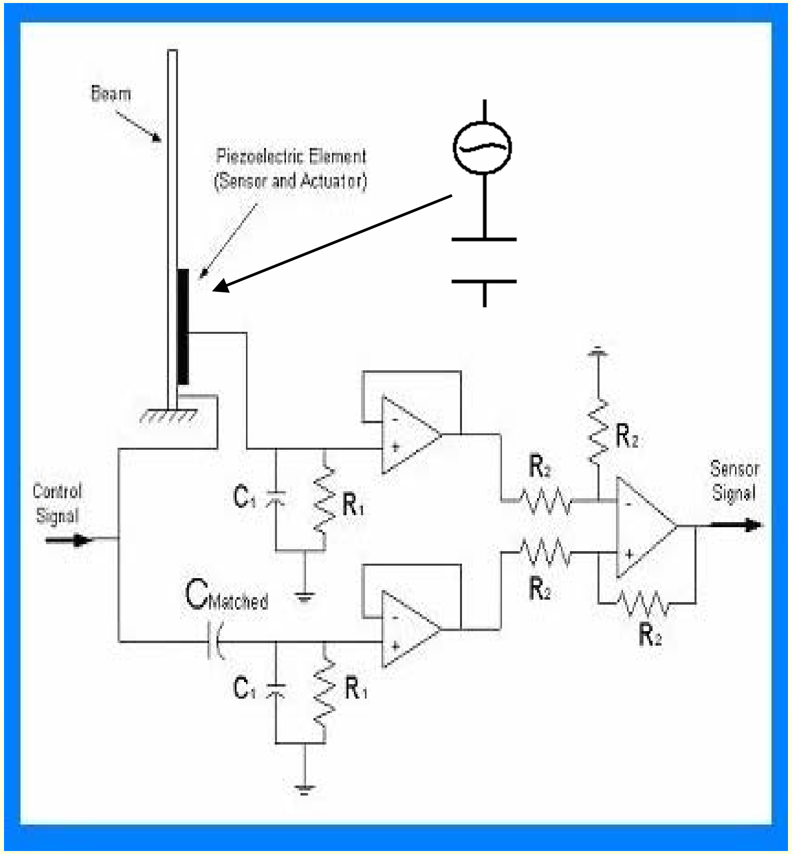


Self-sensing actuators mix sensing and actuator voltages.

The control voltage is larger than the sensor signal.

Bridge circuits are used to separate the two signals.

$$V_s = \frac{C_p \cdot R \cdot s}{R\left(C_1 \cdot s + C_p \cdot s\right)+1} V_c - \frac{C_m \cdot R \cdot s}{R\left(C_1 \cdot s + C_m \cdot s\right)+1} V_c + \frac{C_p \cdot R \cdot s}{R\left(C_1 \cdot s + C_p \cdot s\right)+1} V_p$$



Sodano 2003

Challenge: Bridge circuits that distinguish the control and sensor signals are easily unbalanced.

$$V_s = \frac{C_p \cdot R \cdot s}{R\left(C_1 \cdot s + C_p \cdot s\right) + 1} V_c - \frac{C_m \cdot R \cdot s}{R\left(C_1 \cdot s + C_m \cdot s\right) + 1} V_c + \frac{C_p \cdot R \cdot s}{R\left(C_1 \cdot s + C_p \cdot s\right) + 1} V_p$$

Cp is temperature dependant.

Control instability results from the unbalanced circuit.

Tremendous research efforts have been dedicated to increase stability of the SS actuation.

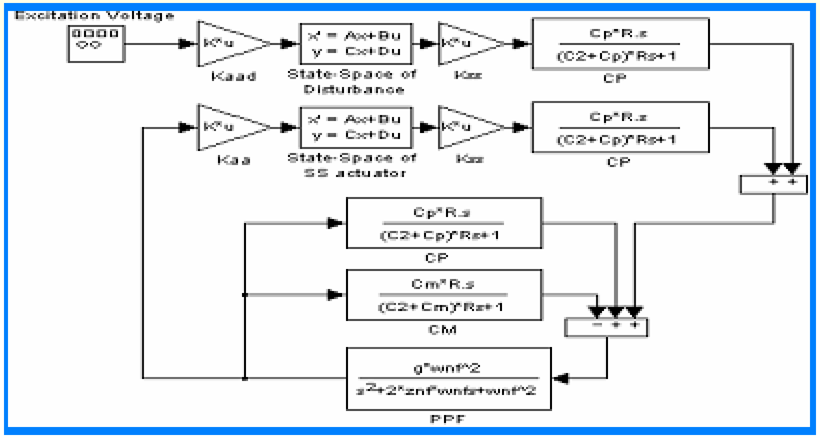
Our goals:
Understand dynamic characteristics
Increase robustness of bridge circuit

This talk will cover modifications made to the bridge circuit to increase stability of the controller.

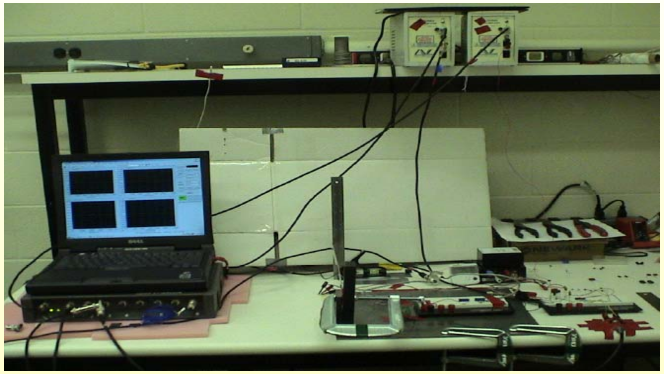
1. Analytical Modeling

$$A=\begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -\omega_1^2 & 0 & 0 & 0 & -2\zeta\omega_1 & 0 & 0 & 0 \\ 0 & -\omega_2^2 & 0 & 0 & 0 & -2\zeta\omega_2 & 0 & 0 \\ 0 & 0 & -\omega_3^2 & 0 & 0 & 0 & -2\zeta\omega_3 & 0 \\ 0 & 0 & 0 & -\omega_4^2 & 0 & 0 & 0 & -2\zeta\omega_4 \end{bmatrix}$$

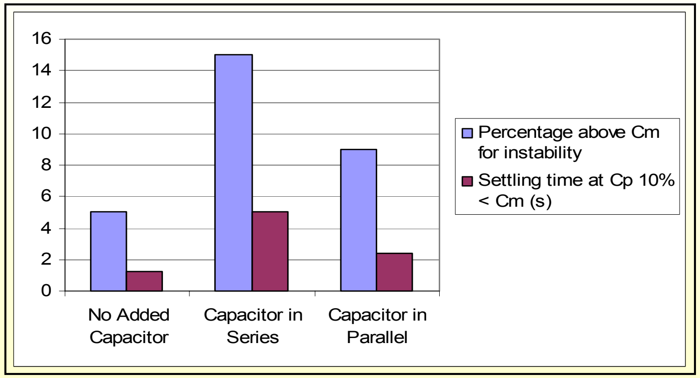
2. Analytical Simulation



3. Experimental Verification

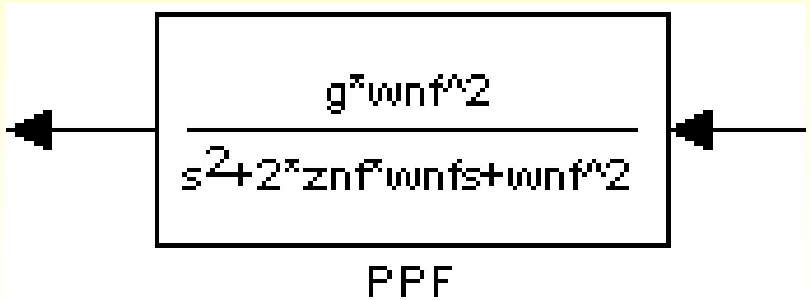


4. Conclusions



A positive position feedback control loop was used for vibration reduction

Control Voltage V_c **Sensor Voltage** V_P



Second Order Transfer Function

Easy to use and very stable

Used displacement as control input

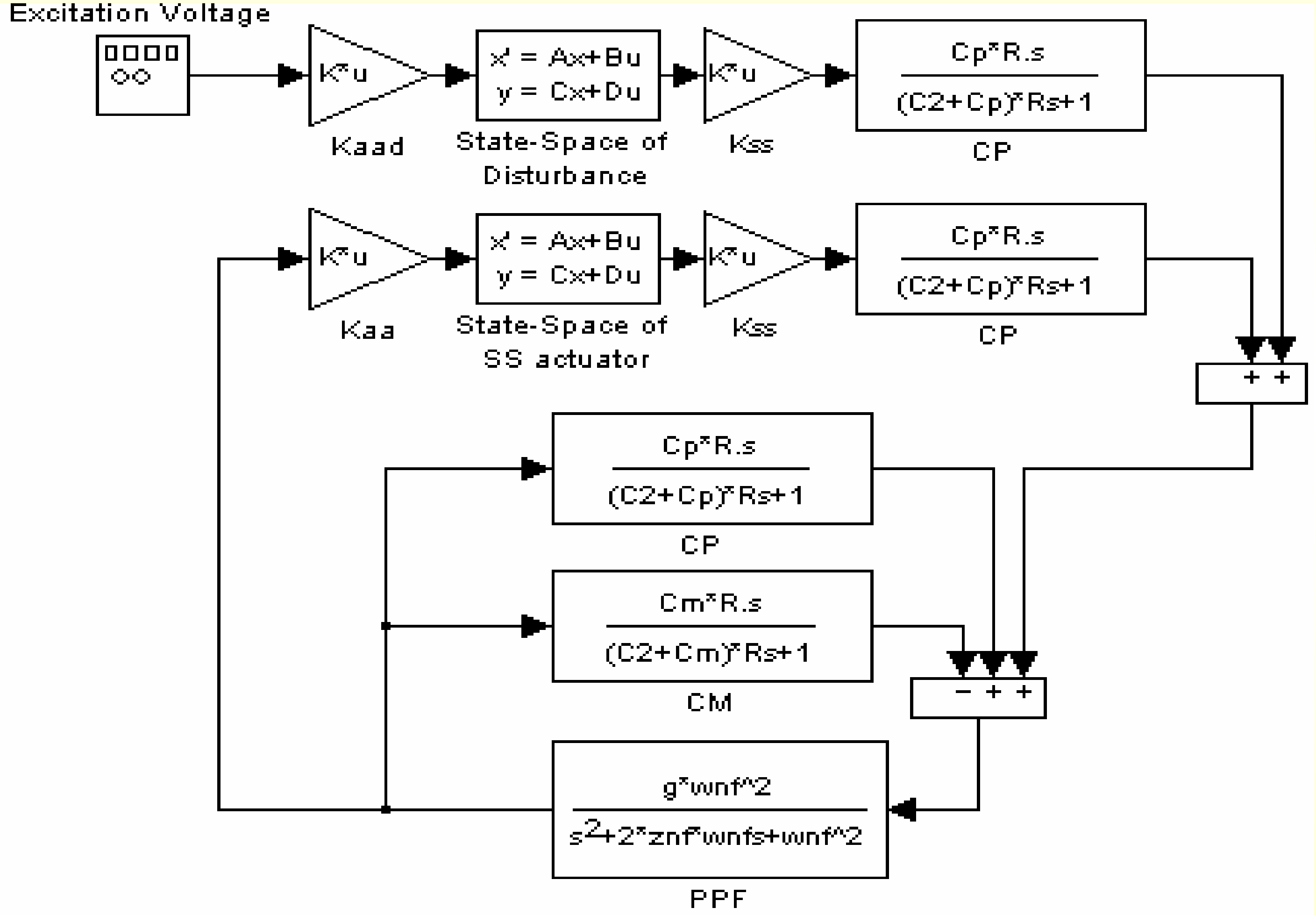
Behaves like tuned absorber

- **Natural frequency** ω_{nf}
- **Damping** z_{nf}
- **Gain** **g (moves pole further left in S-plane)**

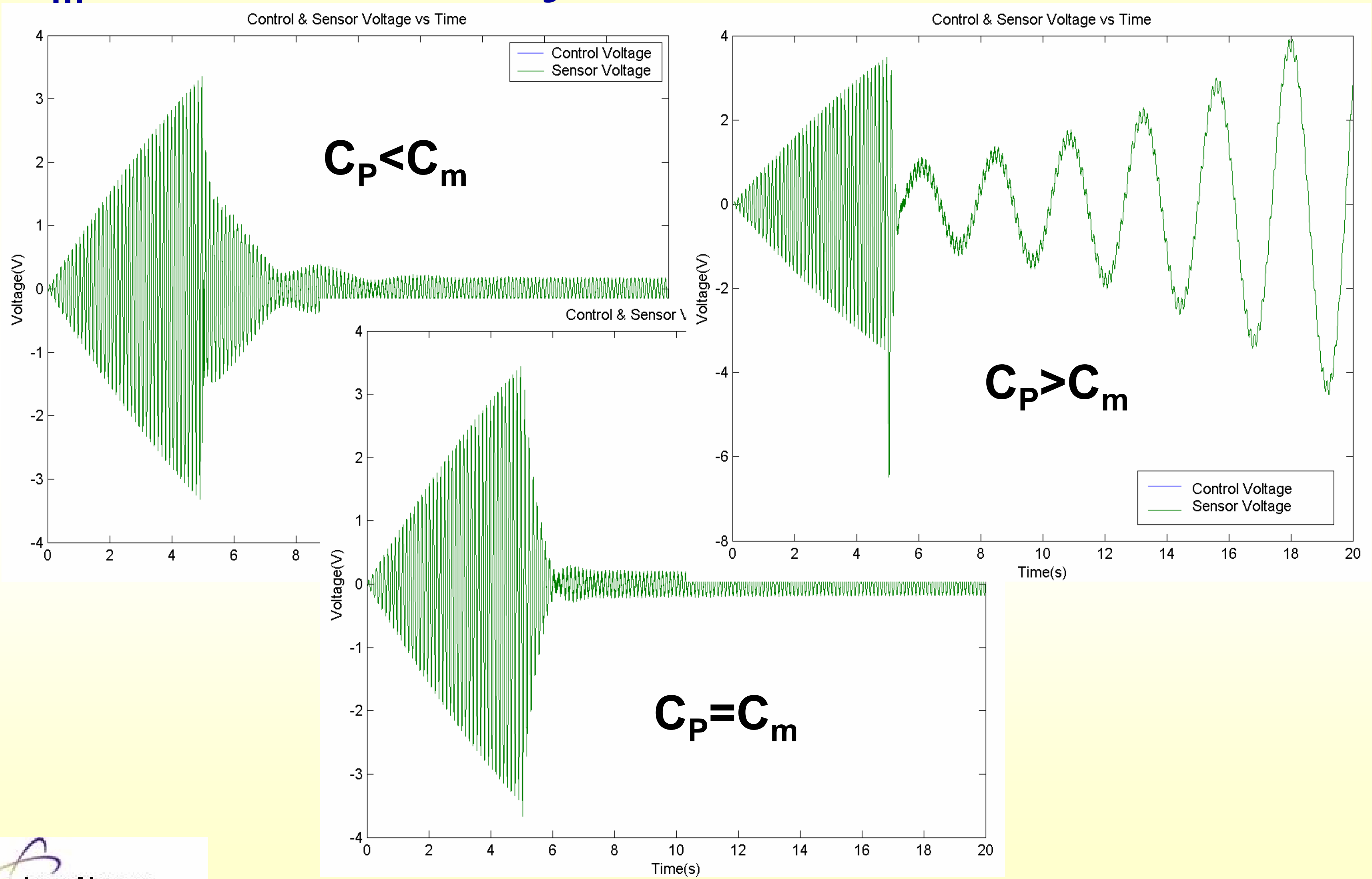
The piezo-beam, self-sensing bridge, and feedback control were modeled analytically

With piezoelectric constitutive and dynamic beam equation

Circuit/PPF transfer functions calculated using impedance

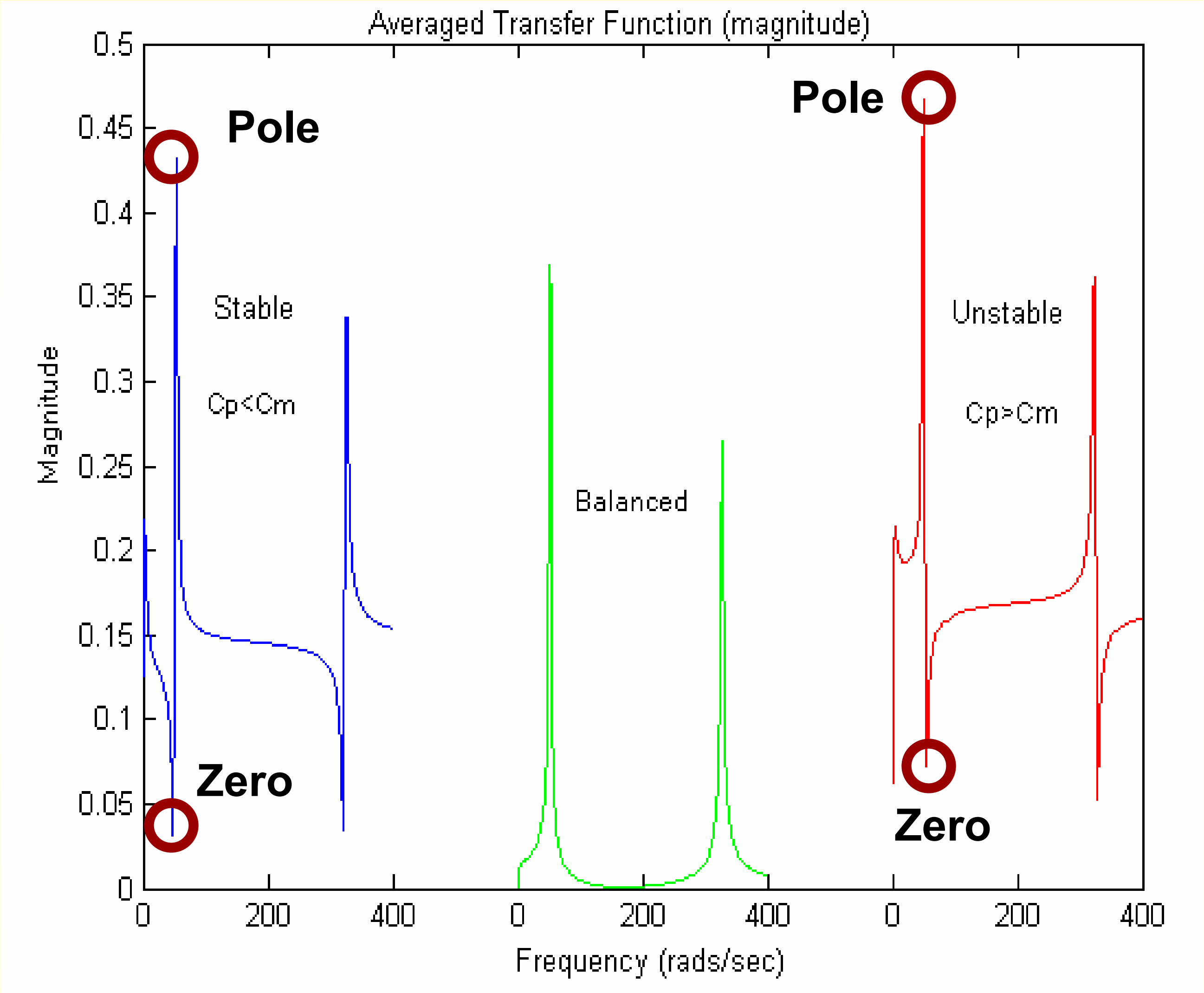


A scenario was developed to identify how C_P and C_m related to stability

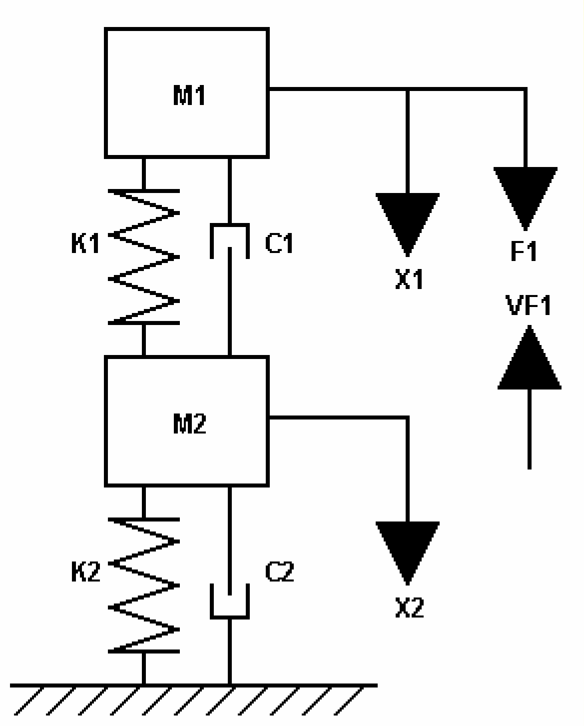


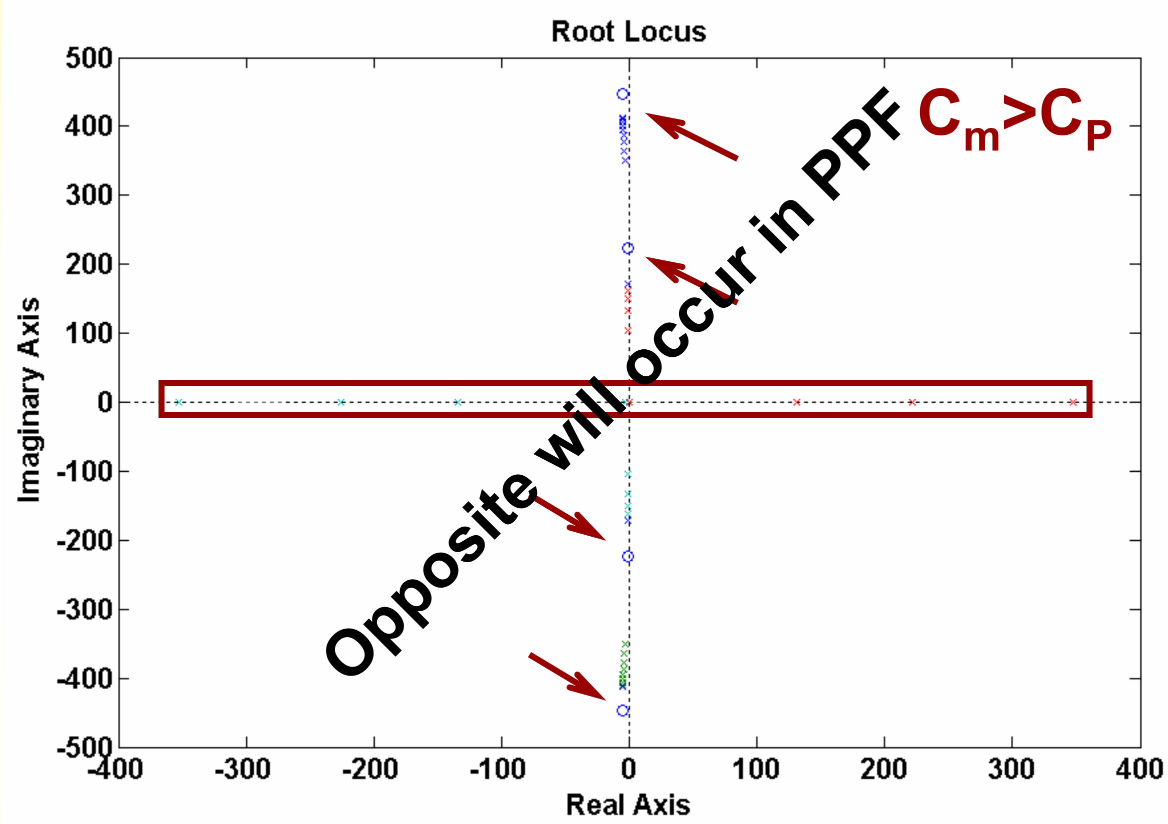
What caused the system to become unstable?

Analytical FRFs obtained via Simulink®



The root loci of a 2 DOF model representing the self-sensing system was studied



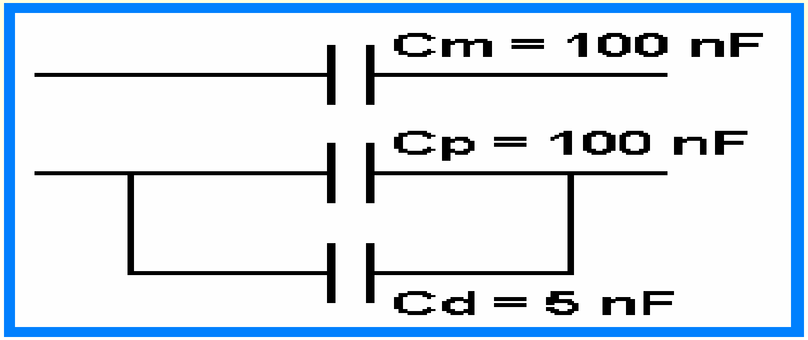


$X1 = V_P$
$F1 = V_C$
$VF1 = V_m$
$V = q/C$

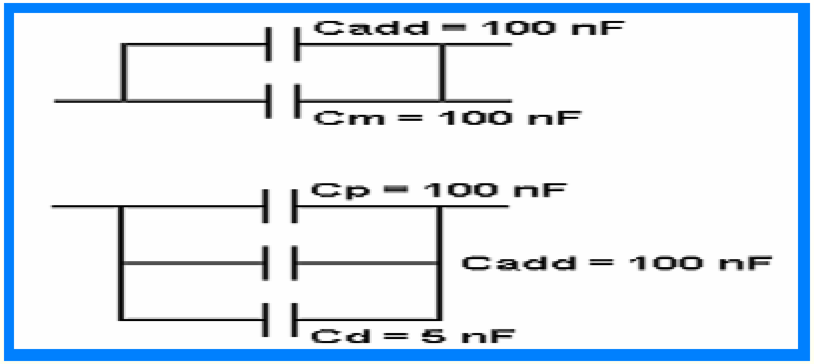
If $C_m = C_P$, then $V_m = V_C$, therefore $X = X1$
If $C_m < C_P$, then $V_m > V_C$, therefore $X = X1 - \alpha F1$
If $C_m > C_P$, then $V_m < V_C$, therefore $X = X1 + \alpha F1$

Our concept for improving the stability of the system was based on minimizing percent mismatch.

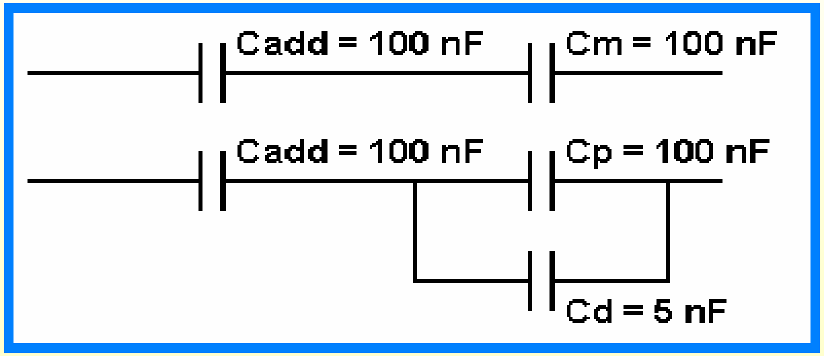
No added capacitor case:
5% mismatch



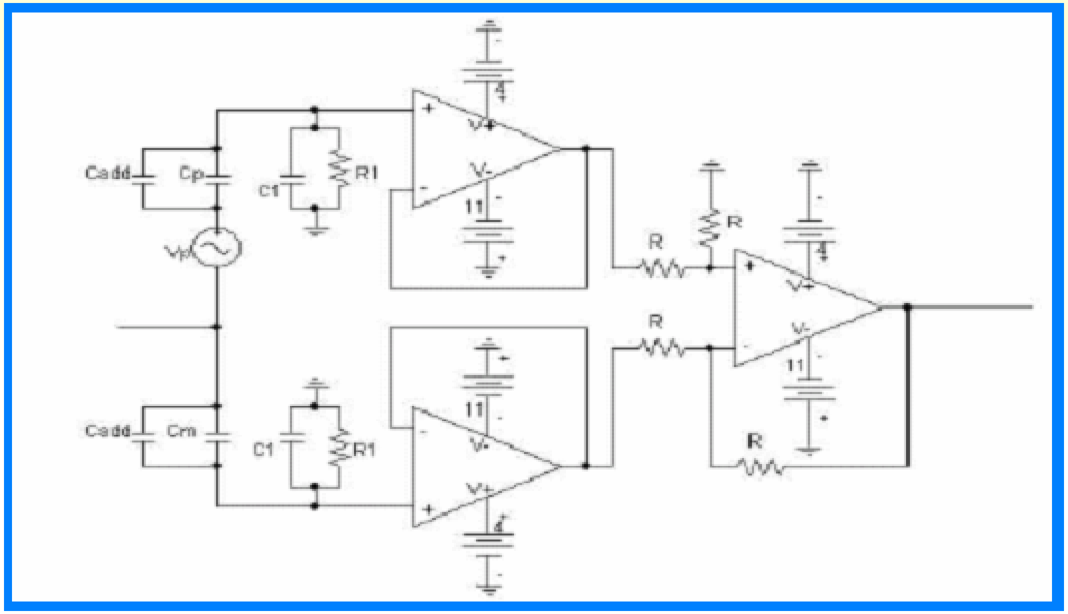
Added capacitor in parallel:
2.5% mismatch



Added capacitor is series:
2.4% mismatch



Simulations were developed to test the added capacitor concept.

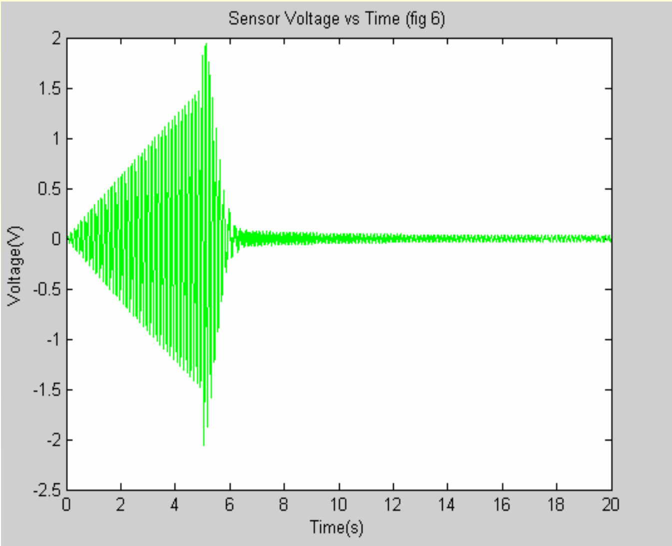


Transfer functions were derived for the modified bridge circuits.

The transfer functions were incorporated into the Simulink® model.

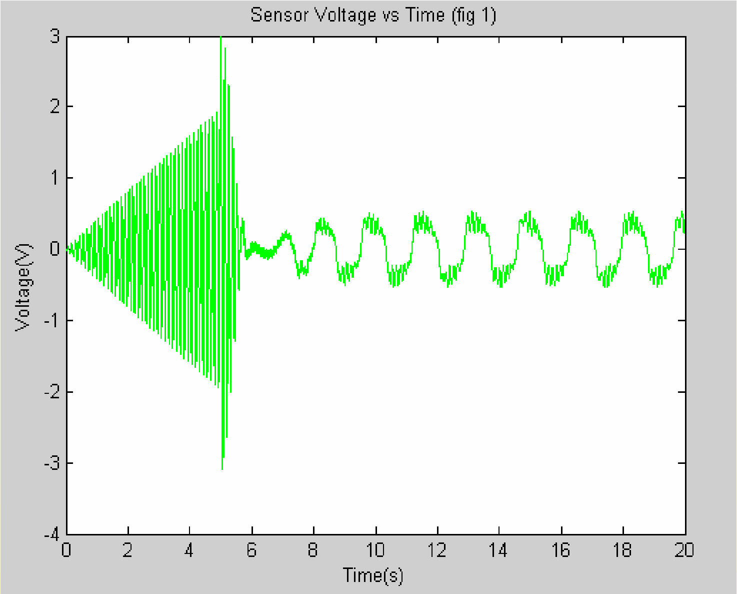
$$V_s = \frac{(C_{add} + C_p)\cdot R_1 \cdot s}{(C_1 + C_{add} + C_p)R_1 \cdot s + 1}\cdot V_c - \frac{(C_{add} + C_{p21})\cdot R_1 \cdot s}{(C_1 + C_{add} + C_{p21})R_1 \cdot s + 1}\cdot V_c + \frac{(C_{add} + C_p)\cdot R_1 \cdot s}{(C_1 + C_{add} + C_p)R_1 \cdot s + 1}\cdot V_c$$

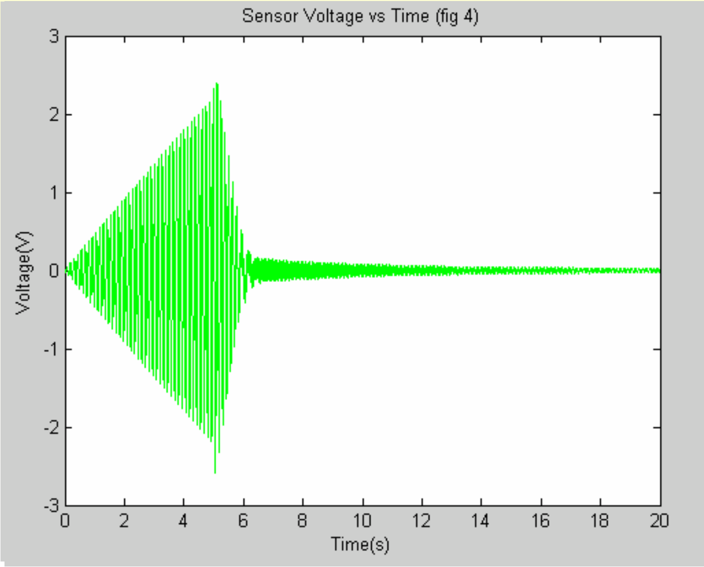
A 6% temperature change: C_{add} are stable



Series add
Stable
t_s=1.4s

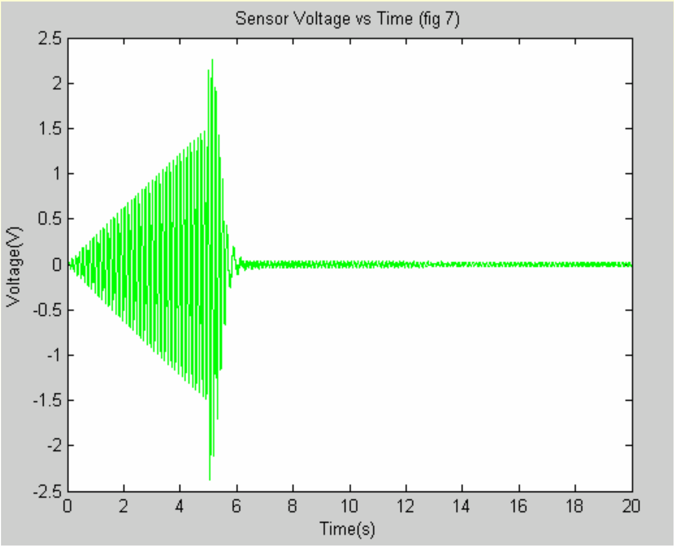
No Add
Unstable





Parallel add
Stable
t_s=1.4s

At 9% temperature change: C_{add} are stable



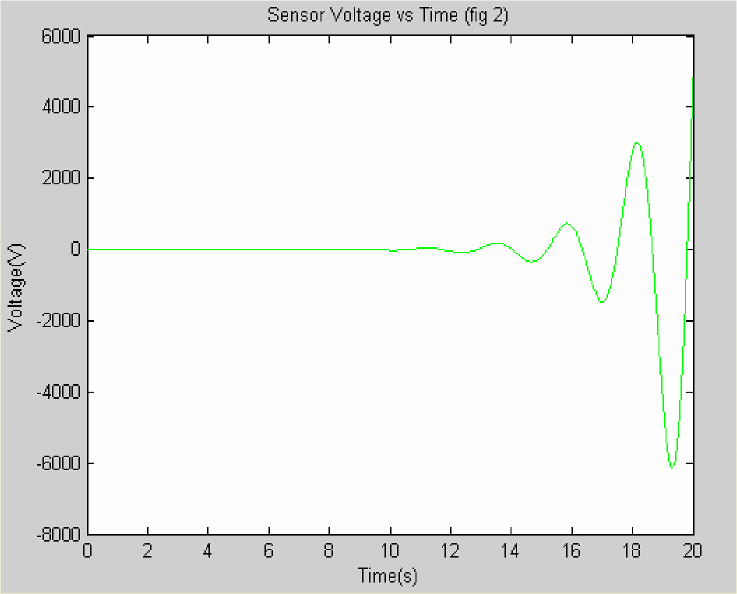
Series add

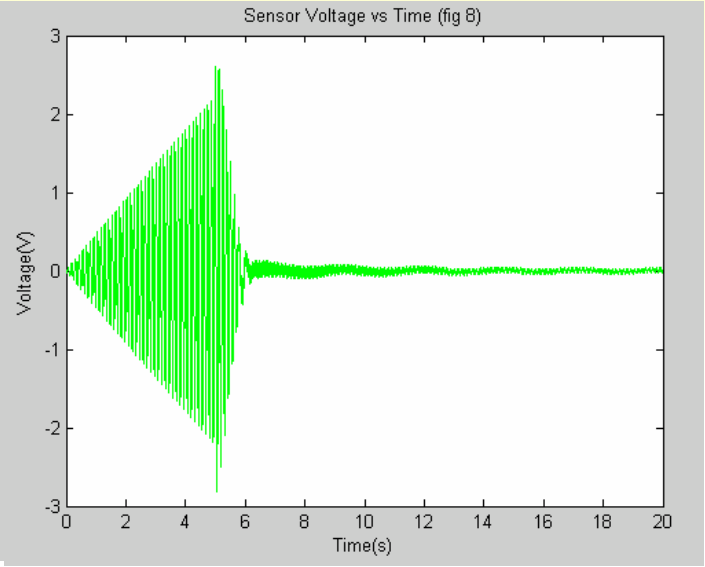
Stable

t_s=1.4s

No Add

Unstable



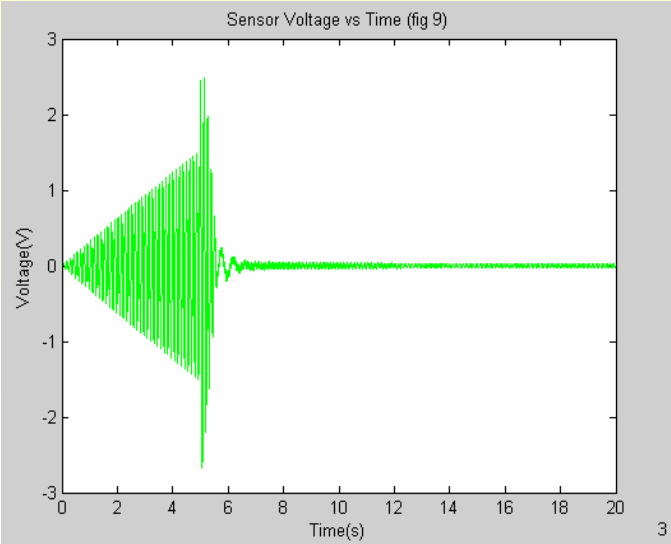


Parallel add

Stable

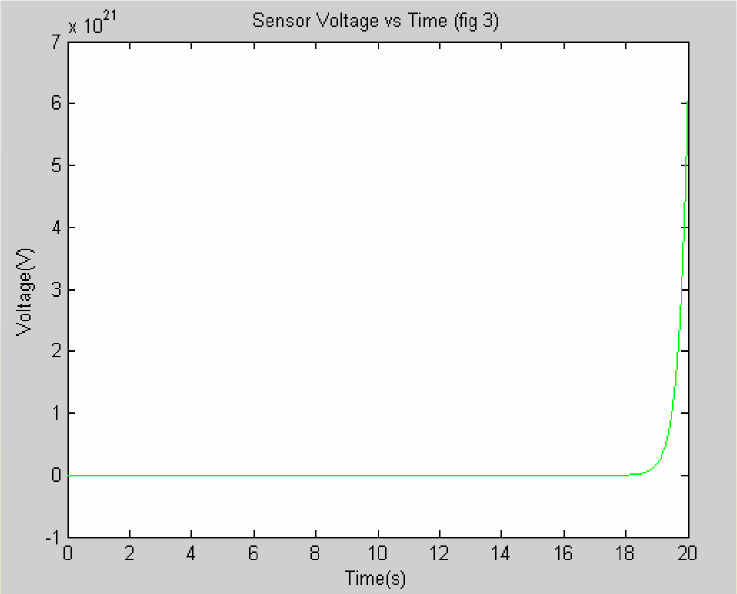
t_s=1.4s

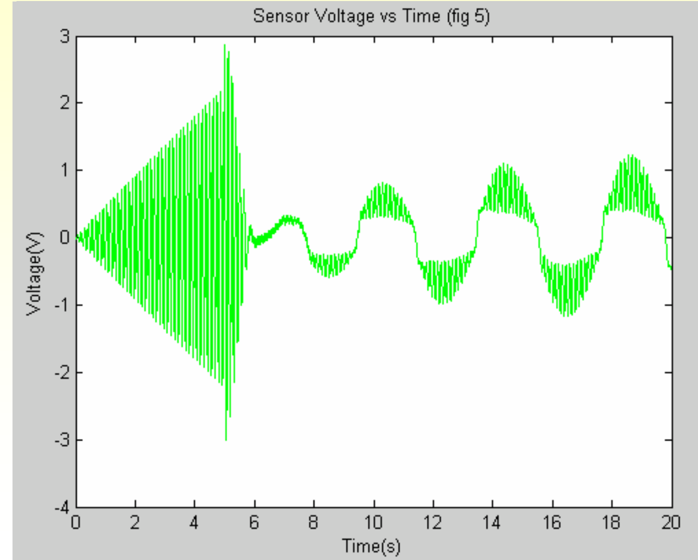
At 12% temperature change: series is stable



Series add
Stable
t_s=2.21s

No Add
Unstable

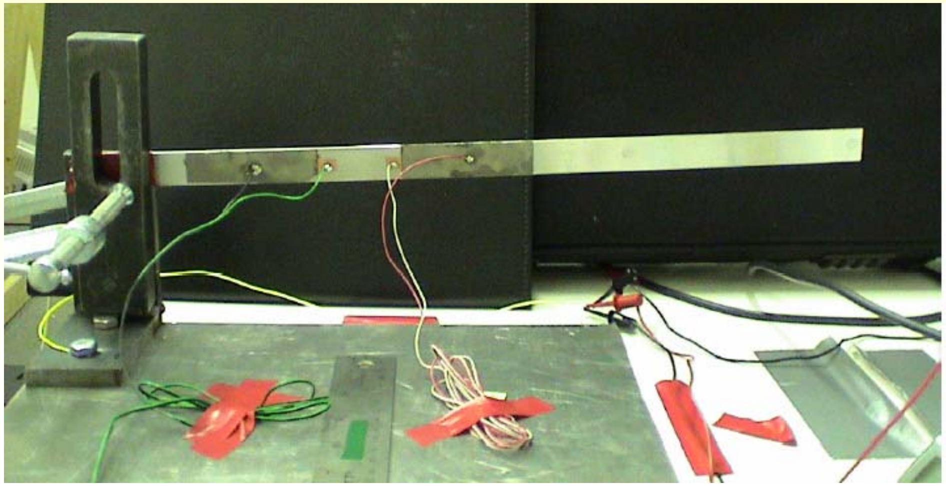


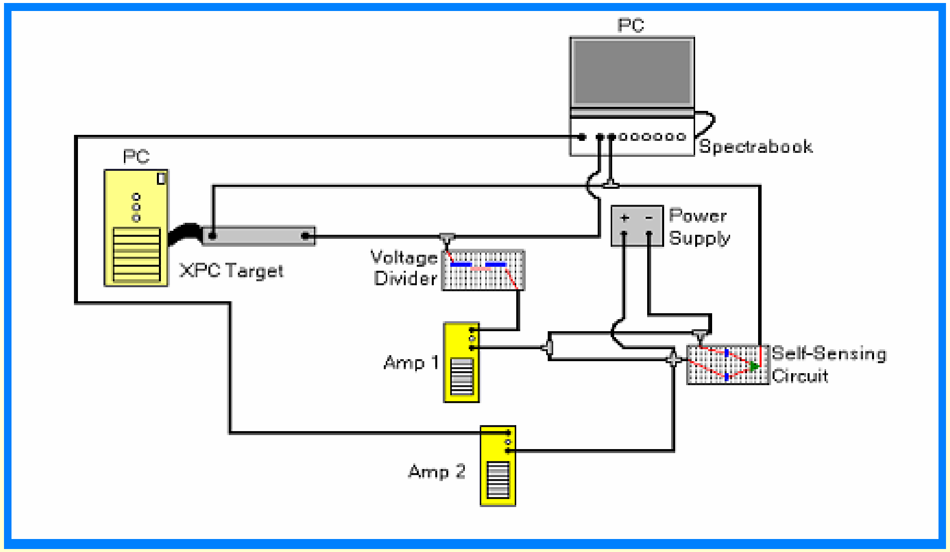


Parallel add
Unstable

The simulation results were verified experimentally by using an aluminum cantilever beam.

Length	0.398 m
Width	0.190 m
Thickness	0.00158 m
Root to Patch 1	0.0180 m
Length Patch 1	0.072 m
Between Patch	0.045 m
Length Patch 2	0.072 m
E	69 E 9
Base	0.335x0.311m
Base thickness	0.005 m



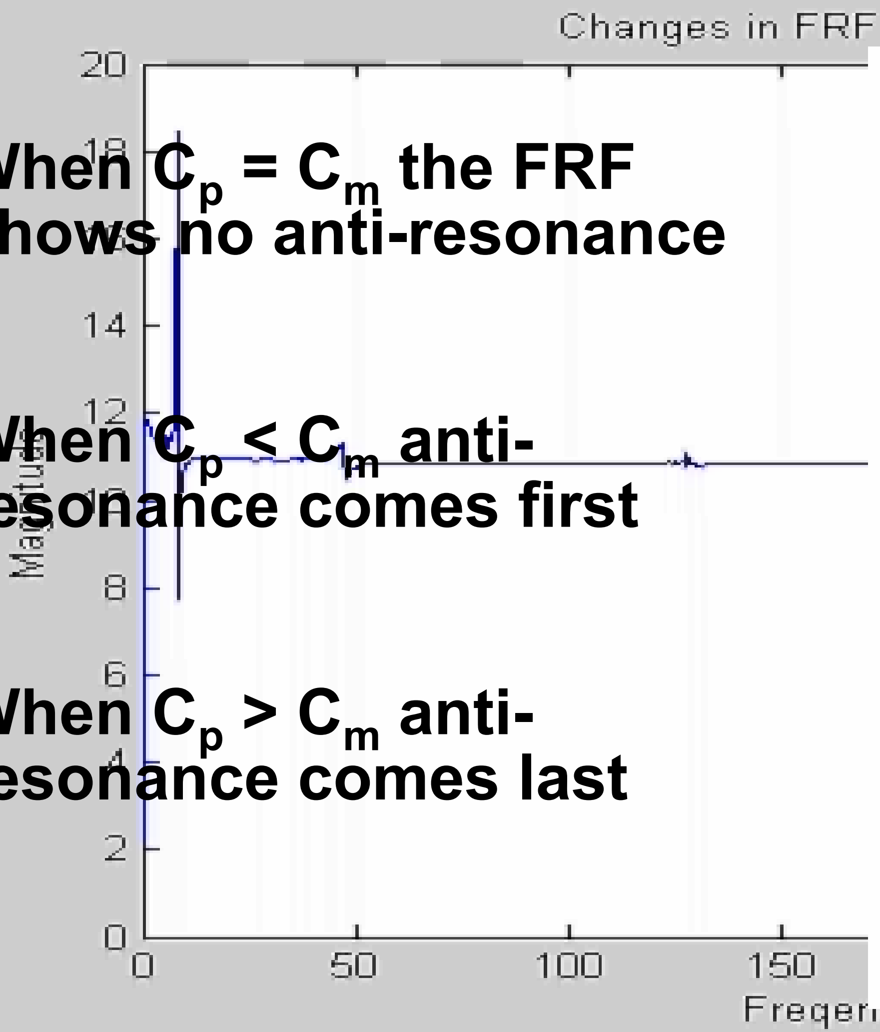


Frequency response functions are related to system stability

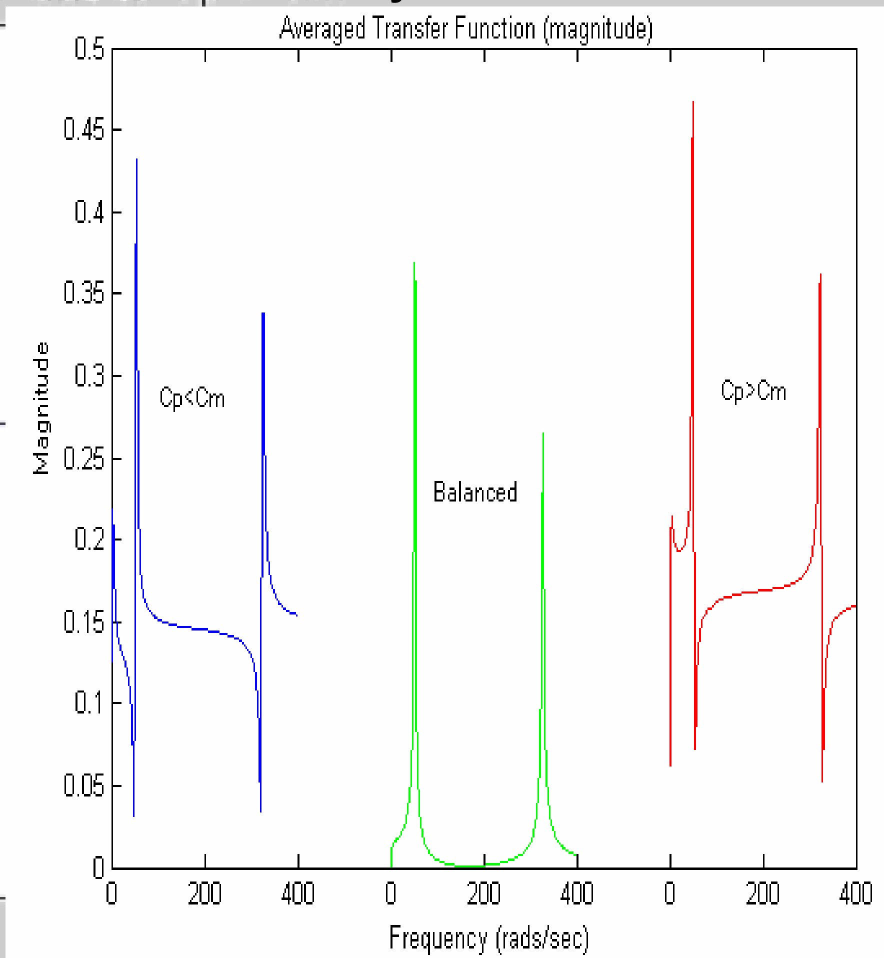
When $C_p = C_m$ the FRF shows no anti-resonance

When $C_p < C_m$ anti-resonance comes first

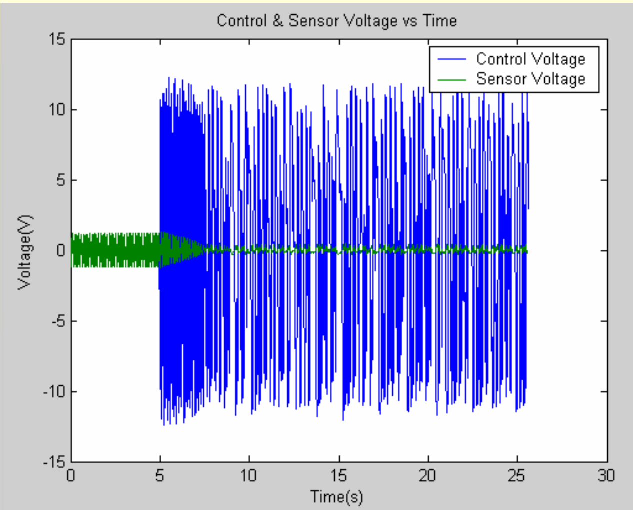
When $C_p > C_m$ anti-resonance comes last

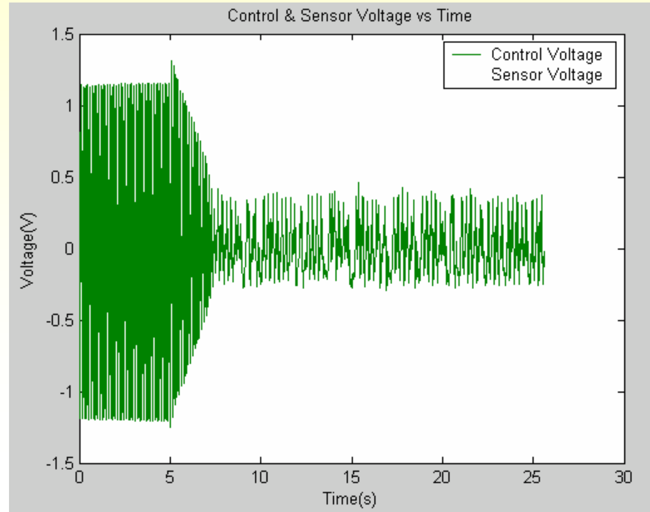


Analytical FRFs

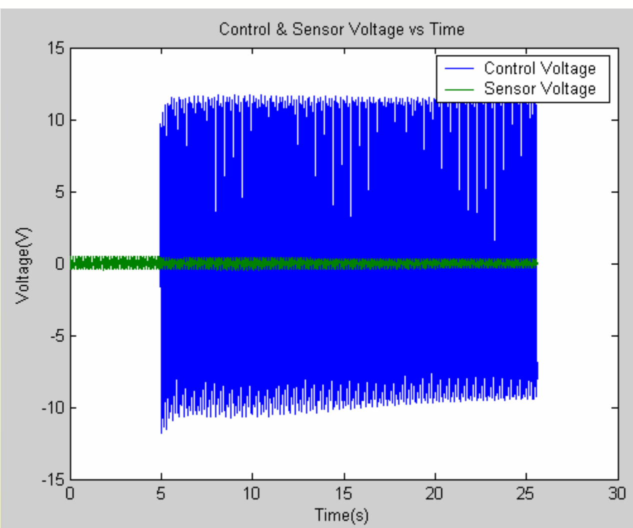


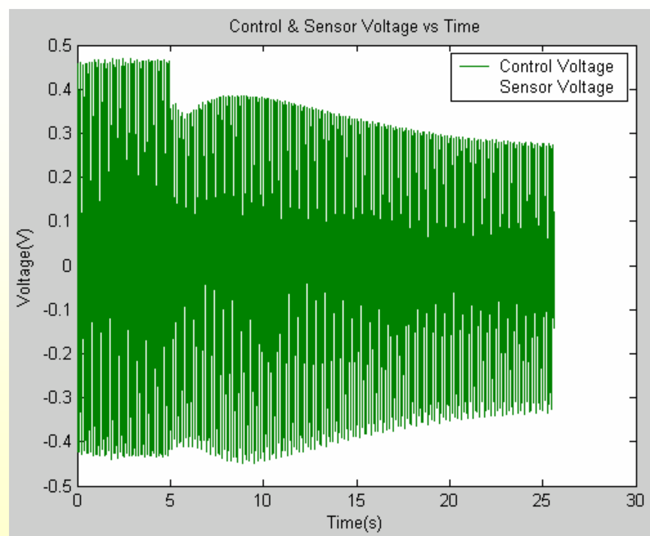
Below are some examples of experimental scenarios that are unstable or ineffective.





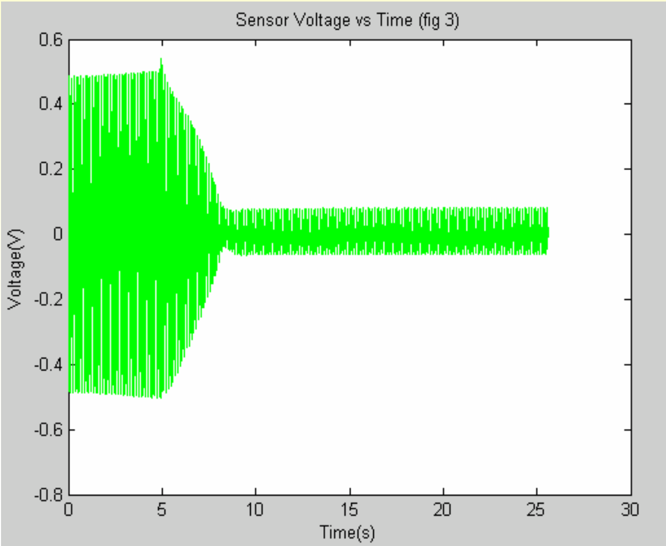
Unstable





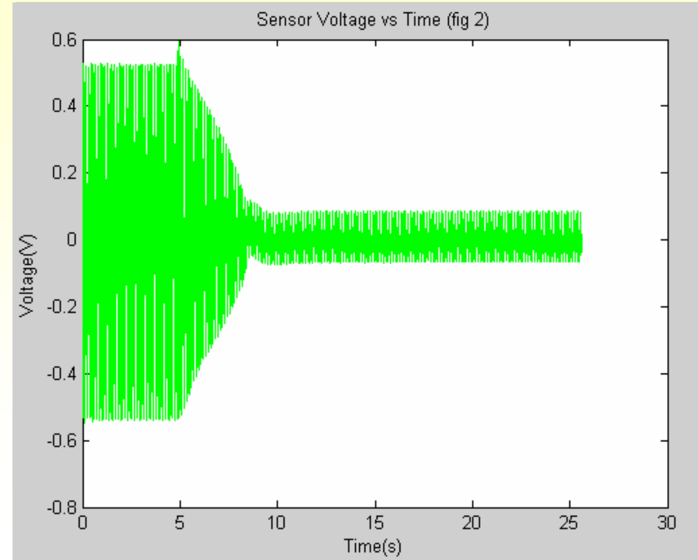
Not Effective

With no temperature disturbance all cases are stable

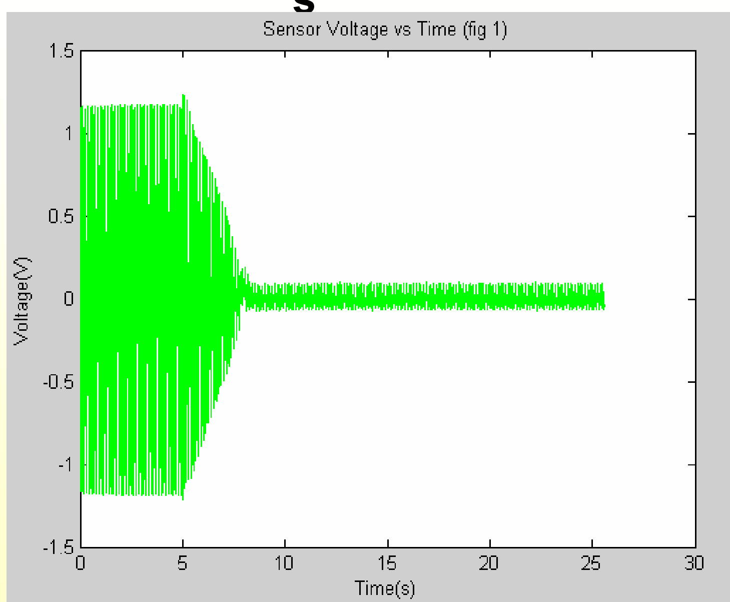


Series add
Stable
t_s=3.35s

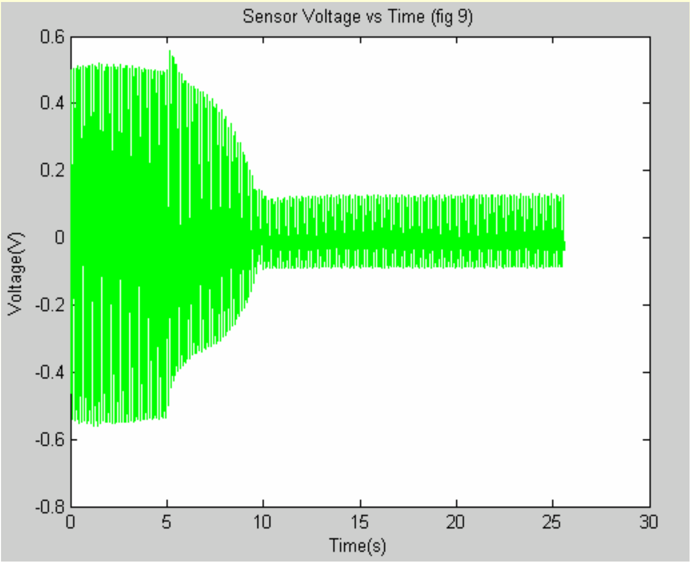
No Add
Stable
t_s=2.81



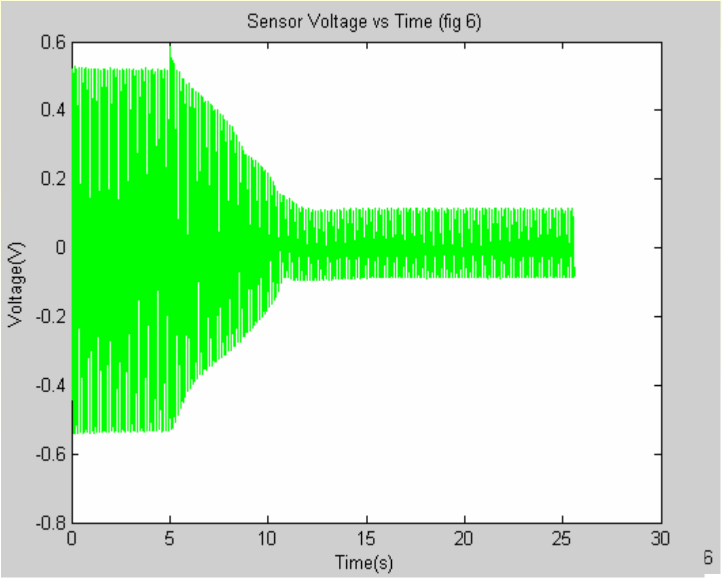
Parallel add
Stable
t_s=3.46



For a 4 nF disturbance: C_{add} creates stability

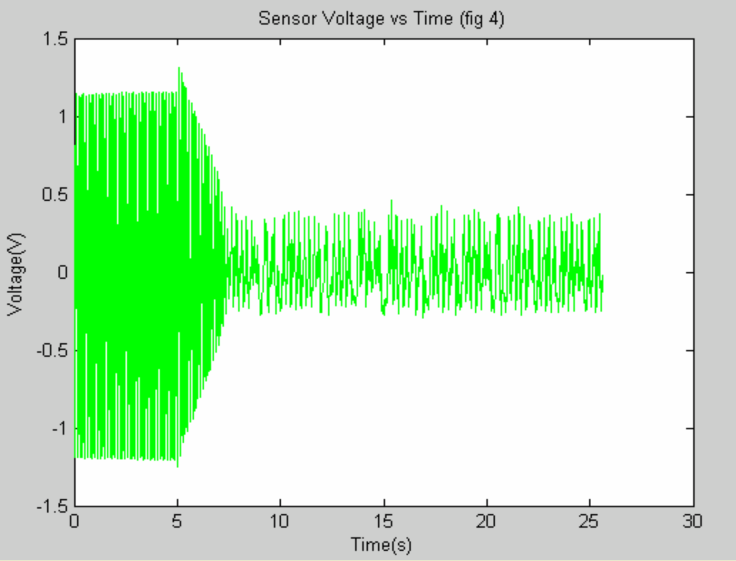


Series add
Stable
t_s = 5.03s



Parallel add
Stable
t_s = 6.08s

No add
Unstable



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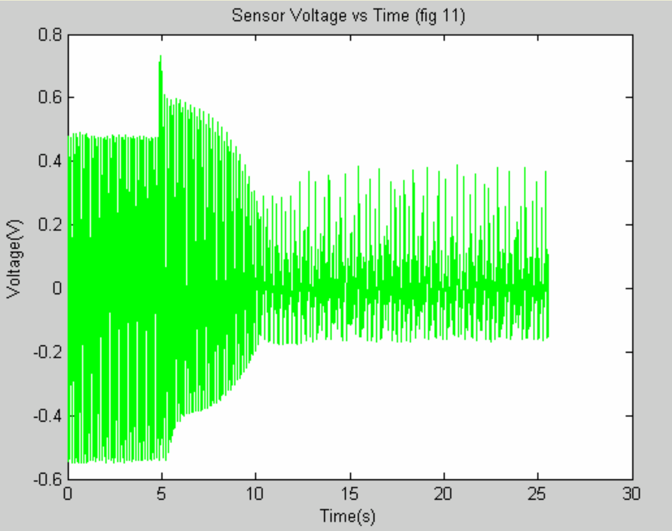
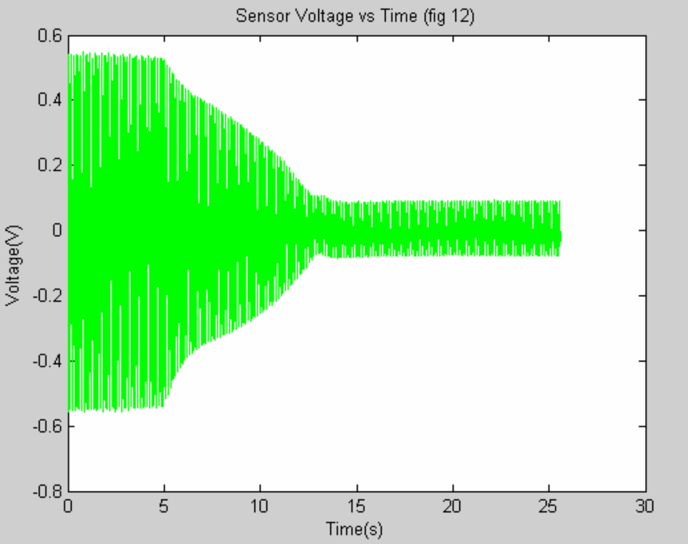
Experimental

10 nF Disturbance: only the parallel case is stable

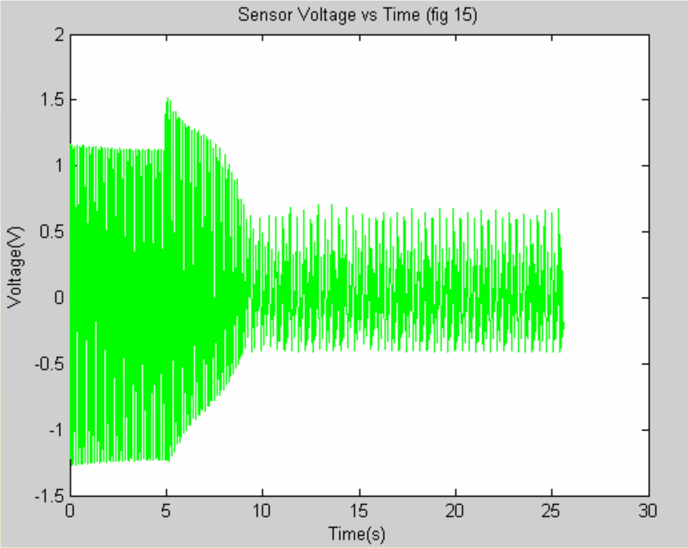


Series add
Unstable



Parallel add
Stable
t_s = 7.70s

No add
Unstable



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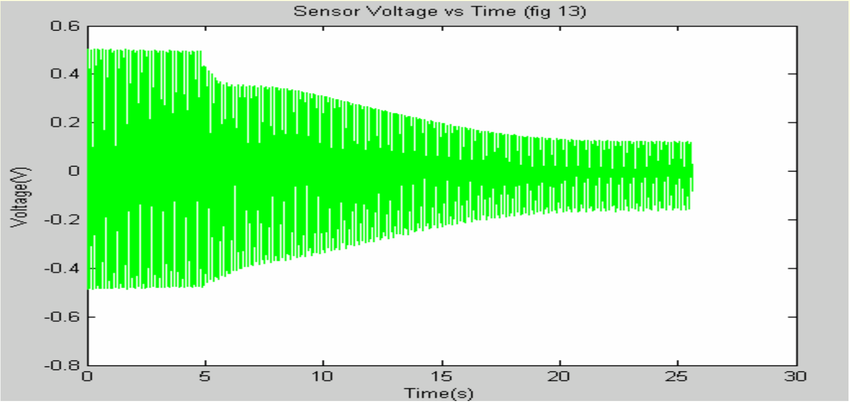
Experimental

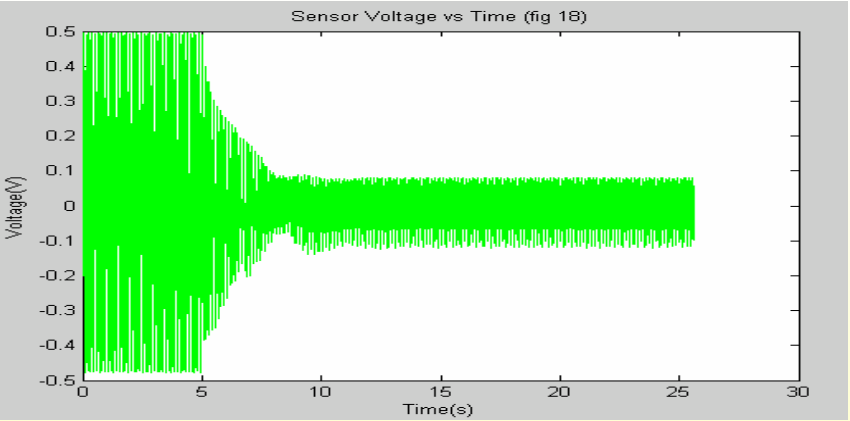
Increasing the power to the amplifier makes the modified circuits more effective.

The loss of effectiveness is most prevalent when $C_m > C_p$



Low Power: t_s= 7.7s

Settling time can be decreased by increasing control power.



High Power: t_s= 3.0s

Conclusions & Contributions

Dynamic characteristics of the self-sensing actuation was quantified for the first time in literature.

Two new design schemes have increased control stability, which makes self-sensing more commercially viable.

The effectiveness of the two design schemes can be enhanced at the cost of increased power to the controller.

Both new design schemes were validated experimentally.

Recommendations

What is the optimal value of the added capacitor?

Quantify the tradeoff between stability (temperature resistance) and effectiveness (vibration reduction).

Applying this technique to complex and real-scale structures.

Use this technique with damage detection schemes.

Acknowledgements

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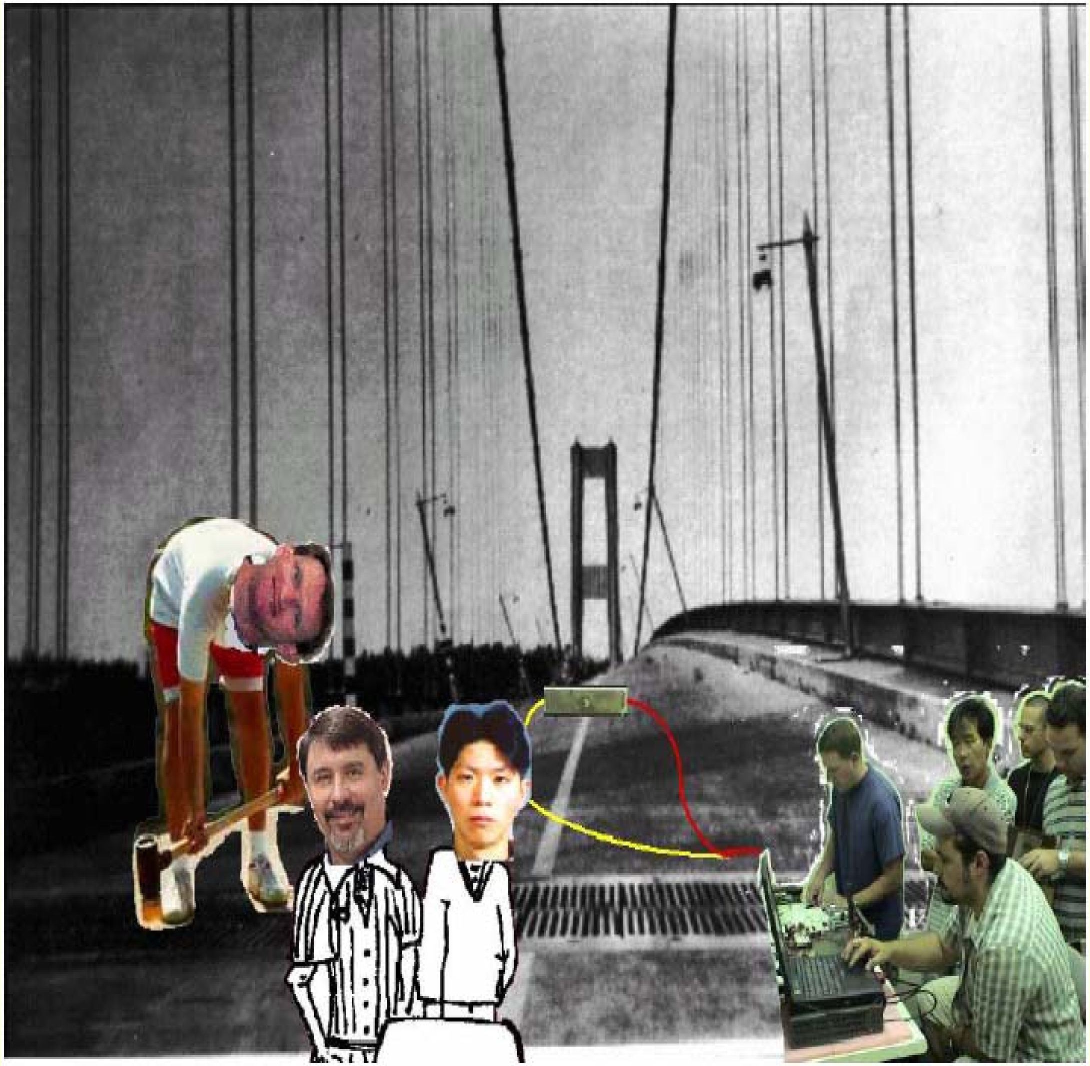
Dr. Charles Farrar
Dr. Pete Avitabile

Software Suppliers
-MatLab®
-Simulink®

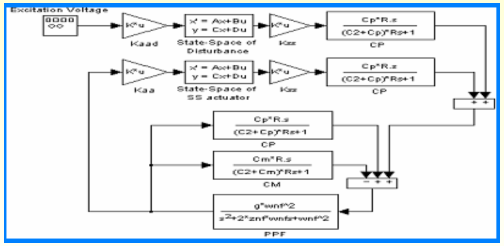


The real DSS

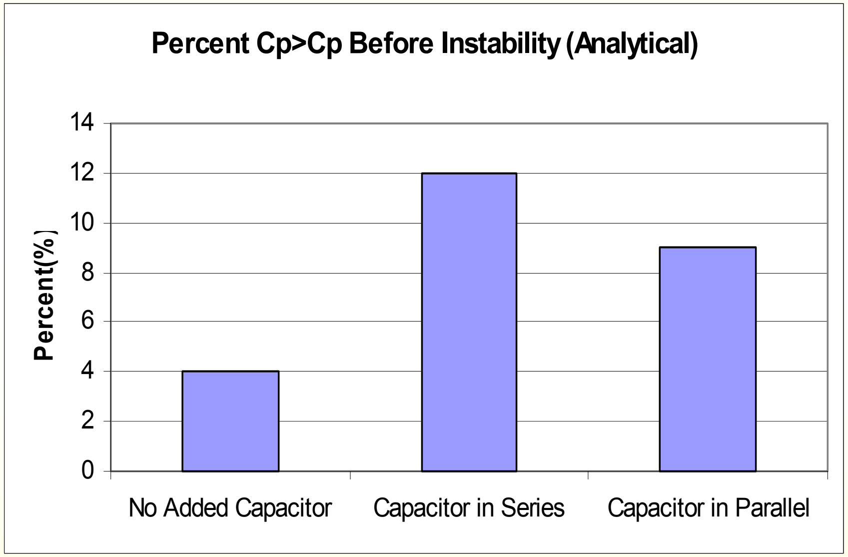
Questions?

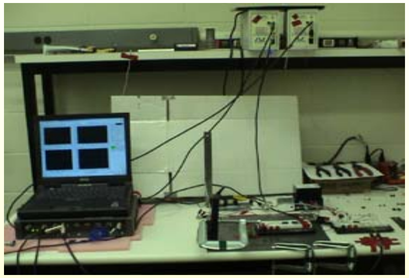
$$A=\begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -\omega_1^2 & 0 & 0 & 0 & -2\zeta\omega_1 & 0 & 0 & 0 \\ 0 & -\omega_2^2 & 0 & 0 & 0 & -2\zeta\omega_2 & 0 & 0 \\ 0 & 0 & -\omega_3^2 & 0 & 0 & 0 & -2\zeta\omega_3 & 0 \\ 0 & 0 & 0 & -\omega_4^2 & 0 & 0 & 0 & -2\zeta\omega_4 \end{bmatrix}$$

Modeling

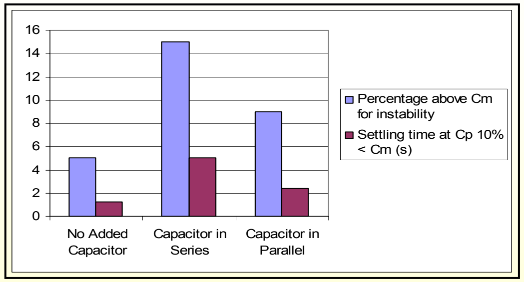


Simulation





Experimental



Conclusions

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